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Investigating Students' Difficulties and Approaches to Solving Buffer Related Problems

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The subject of buffer solutions in chemistry is a challenging concept for students to learn due to its abstract nature. The difficulties that students face in learning about buffer solutions can lead to poor performance and alternative conceptions about the topic. The development of successful conceptual understanding to solve buffer solution problems requires that students have factual knowledge, procedural knowledge, and conceptual knowledge about the topic. This research project of the City College of New York (a minority-serving, public, urban, commuter institution) investigates difficulties that students experience in learning about buffer solutions and approaches that they rely on to solve buffer-related problems. The research method employed a survey comprised of a Likert-type and open-ended questions was used to assess the understanding of 102 participants. The research results indicate that the principal barrier to learning about buffer solutions is students' dependence on formulaic problem solving and calculator use instead of reliance on conceptual understanding. Furthermore, students face difficulties memorizing a significant number of complicated formulas and equations necessary to solving buffer problems. The dominance of student strategies based on plug and chug problem solving likely hinders the development of conceptual understanding. We recommend that instructors need to be familiar with and address difficulties and alternative conceptions students have about buffer solutions.

Keywords: alternative conceptions, buffers, algorithmic problem-solving, learning

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INTRODUCTION

General chemistry courses are often taught enrollment classes taught by traditional lecture format. Students who are taught under a traditional teacher centered approach have shown difficulty in critical thinking and often fail to integrate their acquired knowledge leading to misunderstandings and low academic performance (Acar & Tarhan, 2008; Felder, 1996; Herron, 1996; Nakhleh, 1992; Itzkovich et al., 2020). Researchers have reported (Ben-Zvi et al., 1986: Oborne & Cosgrove, 1983) that students tend to correctly answer questions presented to them but are unable to explain why their answers are correct. Lack of development of conceptual understanding can hinder learning of other related concepts.

Before receiving an education in the sciences students create their theories about the way the world works which are often contrary to theories created by scientists (Osborne & Freyberg, 1985). These self-constructed conceptions are referred to in education literature as misconceptions or alternative conceptions (Krishnan & Howe, 1994; Demiricioglu et al., 2001). These findings indicate that students have difficulty understanding abstract concepts leading them to alternative conceptions. It is important to address alternative conceptions students may have because they affect students' abilities to gain knowledge and connect it to the information, they have already learned thus hindering the formation of new knowledge (Chin, 2001). Many factors can contribute to the development of alternative conceptions students develop such as everyday experiences (Head, 1982), the language traditionally used to teach students (Bergquist & Heikkinen, 1990), teachers, discrepancies in science knowledge between students and teachers (Hodge, 1993), changes in the definitions of chemical terms (Schmidt et al., 2003), and textbooks (Skate et al., 1978). These factors have yet to be addressed in the context of reducing alternative conceptions among students.

Textbooks have been a huge part of school curricula over the years. It has been suggested that textbook language can give rise to alternative conceptions that students develop about many subjects, including chemistry (Pedrosa & Diaz, 2000). To improve chemistry learning, educators need to first improve the curricular resources and the approaches used to teach the material (Pedrosa & Diaz, 2000). A clear issue is an ambiguous manner in which certain words, such as "systems," are used. This lack of clarity leads to a variety of alternative conceptions as proper terminology is critical for proper understanding of complex conceptualizations required to solve problems (Pedrosa & Diaz, 2000). Additionally, textbooks usually display only one method for solving problems, the direct application of a formula to generate a mathematical result. Such a mathematical abstraction leaves students without a reason or justification for their answer (Quilez, 2004) resulting in an ability to solve problems without an understanding of the concepts behind the equations. In turn, this method emphasizes quantitative results over qualitative reasoning. Based on this idea, some researchers (Gabel et al., 1984) warned that without proper understanding of chemical concepts students would continue to do "mindless manipulations of mathematical equations."

Students face many learning challenges that hinder students' learning of chemistry concepts. Some of these learning difficulties are acquired when students fail to fully

understand a concept may result from either of two things: the nature of a student's knowledge or the inadequacy of this knowledge as it pertains to the concept in question (Kempa, 1991). Five areas in chemistry have been identified as being the most difficult for students to learn; the mole concept, reaction stoichiometry, oxidation and reduction, chemical equilibrium (Hackling & Garnett, 1985), and acids and bases (Demircioglu et al., 2005). Most of these topics are not only interrelated but are fundamental to understanding the nature of chemistry. Alternative conceptions in these areas will therefore create problems for students as they attempt to progress through upper-level courses.

One of the most important and complex elements of chemistry is the concept of chemical equilibrium (Kousathana & Tsaparlis, 2002). Griffiths (1994) identified a total of twenty alternative conceptions associated with chemical equilibrium many of which relate to the conceptual aspects (Kousathana & Tsaparlis, 2002) of chemical equilibrium. Kirik and Boz (2012) attribute these conceptual difficulties to the abstract nature of the idea of chemical equilibrium. This abstract nature causes students to make assumptions unbeknownst to their teachers leading to alternative conceptions. Student performance in both conceptual and computational problems about chemical equilibrium was compared by Niaz (1995) who found that students that performed better on the conceptual problems also performed better on the computational problems (Niaz, 1995). Understanding chemical equilibrium concepts can improve meaningful learning of buffer solution problems.

Problems involving chemical equilibrium tend to incorporate other concepts such as reaction stoichiometry causing significant difficulties for students. These problems are difficult because they require analogical reasoning, something that most students lack or have not developed fully (Shayer, 1991). It has also been found that students' alternative conceptions in chemical equilibrium are directly related to their experience in the classroom learning the material (Crosby, 1987). Both students and teachers found the concept of chemical equilibrium difficult to learn and teach respectively (Finley et al., 1982). Quilez and Solaz (1995) suggested that to effectively teach the abstract concept of chemical equilibrium it is necessary to effectively consider the prerequisites needed to learn it. The difficulty students experience solving chemical equilibrium problems is not merely with the mathematical calculations (Hudle & Pillay, 1996), but is more directly related to their improper understanding of the concept while algorithmically applying the formulas they've been taught (Bergquist & Heikkinen, 1990). Students who depend on algorithmic problem solving less likely to develop conceptual understanding of chemistry concepts and gain meaningful learning.

It is clear that students solving chemistry problems like those involving chemical equilibrium typically rely on the memorization of fixed reasoning patterns resulting in minimized understanding (Kousathana & Tsaparlis, 2002). This pattern is typical of other findings that a majority of students simply solve problems by rote without understanding what they are doing or why they are doing it (Herron, 1996). Assessment questions that allow for students to simply regurgitate information compound this problem by giving the false impression that they a level of understanding that they, in

fact, lack, thus inhibiting the further development of their understanding of chemical concepts. (Monk, 1995). It is thus possible for students to advance academically along with their alternative conceptions in the fundamentals of chemistry (Tsaparlis & Kousathana, 1995).

Pedagogical models are an essential part of teaching chemistry effectively (Justi & Gilbert, 2000; Justi & Gilbert, 2002; Van Driel & Verloop, 2002). Such models are used because they connect the reality we observe with the educational theories we advocate (Gilbert et al., 2000). Three models have been described for teaching students about acid/base behavior. When analyzing acid/base reactions students often used parts of each model to explain what was happening without the ability to discriminate between the parts of the models that accurately described the reactions and those that didn't. This issue was blamed on the complexity of the models which resulted in difficulty understanding acids and bases (Carr, 1984). Textbooks often compound the confusion generated by these complicated models by showing them successively but not indicating how they are related (Wilson, 1998; Drechsler & Schmidt, 2005; Furio-Mas et al., 2005; Gericke & Drechsler, 2006). Teachers then follow the textbooks without developing the connections themselves compounding the difficulty students face. Instructors that simply repeat the models in the textbooks without elucidating their interrelationships may thus further impede student progress by making students believe that there is nothing more for them to comprehend.

Some of the most common alternative conceptions about acids and bases are related to neutralization, the difficulty in mathematical calculations involving pH, the unclear understanding of the dissociation and ionization of an acid, the degree of ionization, and buffer solutions (Cartrette & Mayo, 2010). Quilez and Solaz, (1995) have reported that both teachers and students found diluting a weak acid solution was a difficult problem to solve. Alternative conceptions related to acids and bases have a significant impact on future learning, knowledge construction, problem-solving, and laboratory practices (Cartrette & Mayo, 2010). A specific curriculum was created for "Acids and Bases" using the conceptual change approach as an attempt to address alternative conceptions that students might have on the topic. It was found that those students taught with this curriculum had higher achievement levels than those taught with what is known as the conventional method (Hand & Treagust, 1991). Incorporating different teaching strategies that is grounded in constructivism and collaborative learning in chemistry can be more effective in promoting learning and student performance when compared to traditional teaching approach (Sugano & Nabua, 2020).

Most general chemistry courses dedicate multiple days to modeling buffer calculations because it is believed to be a topic that students (whether chemistry or biology majors) must understand well. Despite of the time and effort dedicated to it, students still struggle with the concept of buffers and the calculations related to them (Orgill & Sutherland, 2008). Even students who are comfortable solving other problems using algorithms find it difficult to solve buffer problems (Urbansky & Schock, 2000). A student must understand the macroscopic, sub-microscopic, and symbolic perspectives on buffers in order to truly grasp them conceptually (Johnstone, 1991) and then be able

to integrate those concepts (Talanquer, 2011). This is an important aspect of a student's science education because without such a fundamental understanding of the basics it will impossible to understand more advanced topics. Using three dimensional visualization of the process that is taking place can improve conceptual understanding. Researchers report that students who rely on 3D visualization in learning exhibit positive attitudes towards science and improved critical thinking skills (Astuti et al., 2020)

It has been found that like chemical equilibrium problems, buffer problems, are not often integrated on different levels because they are taught in the most abstract form first thus creating confusion in students (Raviolo, 2001). Chemistry learning is challenging for students due to its highly conceptual and abstract nature (Kirik & Boz, 2012). Confusion could also be caused by instructors focusing on calculations related to buffers in class and on exams. This focus could cause students to end up thinking that their ability to solve buffer problems is the same as their understanding of buffers and how they function (Orgill & Sutherland, 2008). Furthermore, students often erroneously believe that solving more will help them to understand the concept that is being applied in an algorithm they have memorized leading to a good grade in the course (Lyall, 2005). Students do not realize that without the proper conceptual background they are likely to apply their algorithms in inappropriate situations (Gordus, 1991; Hawkes, 1996).

In order to understand buffers, it is necessary to first understand chemical equilibrium and acid/base chemistry (Sheppard, 2006; Bilgin & Geban, 2006). Various studies (Johnstone, 1991; Orgill & Sutherland, 2008; Quilez & Solaz, 1995; Raviolo, 2001) have revealed that students understand very little about buffers. In a landmark study, Orgill and Sutherland (2008) investigated student understanding of the principles of buffering solutions. When asked about what a buffer is chemically most students could not specify what it was besides an acid/base. They could not distinguish between the terms associated with buffers such as strong/weak bases in relation to the buffers themselves. Students in this study primarily approached buffer problems as mathematical problems and failed to consider the chemical species involved. It was clear that students had difficulty in interpreting and solving buffer problems because of insufficient understanding of the relevant terminology. Students could not correlate the appropriate chemistry terms with the variables of the Henderson-Haselbalch equation, or makes use of important information given in a problem and failing to determine a correct answer. A common complaint among students was that many buffer questions looked quite similar even though they required solution methods. Such a complaint is due to the students' lack of conceptual knowledge about buffers. Students were fundamentally unable to realize that they lacked this conceptual knowledge and that the reason they were unable to answer the questions was this lack of understanding.

Our guiding research questions are: What difficulties do students experience in understanding buffer solutions? What approaches do students use to solve buffer-related problems? and Do students rely on algorithmic problem-solving instead of conceptual understanding in solving buffer problems?

METHODS

Participants and Context of study

This project was designed to investigate the challenges that students face in learning about buffer-related problems and the approaches they use to solve these problems. The project took place at the City College of New York (CCNY) during the spring and fall semesters of 2020. The City College of New York is an urban minority-serving public college with a commuter student body. All participants in this project had successfully completed a year of General Chemistry course and were enrolled in upper-level courses at the time they were surveyed. We created a survey made up of both Likert-type and open-ended questions to gather data about student conceptions and practices. The survey was reviewed by two experts in assessment who verified that the questions adequately and objectively evaluated student understanding of buffers. A test-retest reliability analysis produced a reliability coefficient of 0.84 for our survey. The survey was administered to, and collected from 102 participants with approval from the CCNY Internal Review Board (IRB).

Data Analysis

The Likert-type questions were on a five-point scale using numerical values as follows: Strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5). We performed a single factor ANOVA on our Likert-type questions to understand the variability of the student responses to them. Insufficient variability in student responses to a question would indicate that it either did not accurately reflect student experience or that student experience of the issue at hand was too uniform to be informative. The average numerical values of students' responses for each question were calculated and displayed in histograms.

For three of the open-ended questions, we used a rubric to convert the respondents' answers into numerical values ranging from 1 to 5. As in the Likert-type questions these values were averaged and displayed in histograms. Responses to two of these questions were diverse enough that a pie chart was used to display the various student responses.

The ANOVA performed on the Likert-type questions found a P-value $< .001$. This statistically significant result allows us to reject the null hypothesis that there is no variability in student responses to individual questions. Furthermore, the mean square for our data is 16.62 which is much larger than the mean square within the treatments which is 2.23. These results demonstrate that the Likert-type questions are reasonable indicators of student perceptions of the difficulty and solution methods of buffers problems.

FINDINGS AND DISCUSSION

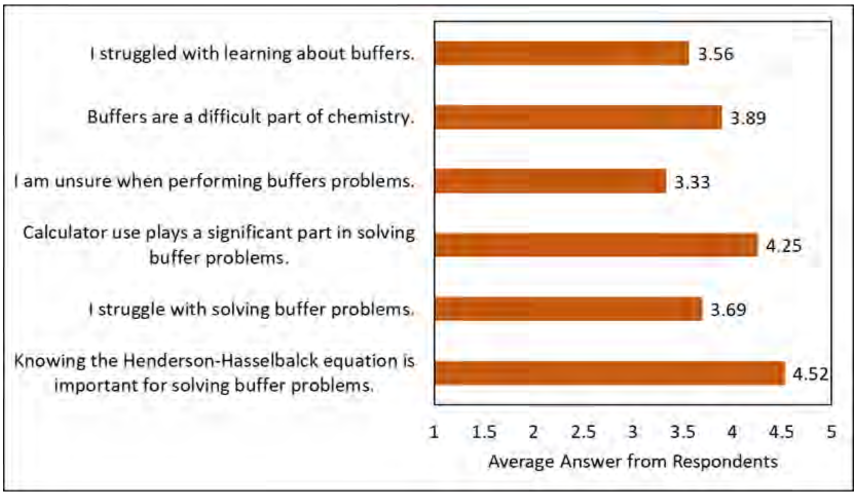

Figure 1
Average responses of students to Likert-type questions in our survey
The range of answers was: strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5).

Responses to our Likert-type questions revealed (Fig. 1) students' perceptions about buffer solution problems. The students surveyed expressed the perception that buffer problems are difficult to solve and that calculators were necessary to achieve a solution. Most importantly, the data indicate that students rely heavily on the Henderson-Hasselbalch equation to solve buffer problems. These findings are contrary to the common practice of analytical chemists who would rely on the equilibrium constant to solve such problems rather than depending on the Henderson-Hasselbalch equation.

Students' perceptions of the importance of calculators and plugging numbers into equations can be detrimental to the development of their conceptual understanding and meaningful learning (Novak, 1984) of the buffer concept. Learning about buffer solutions is considered a complex task because it involves complicated calculations, chemical concepts, and applications. When students create conceptions that differ from the norms of the scientific community they face significant problems as they progress though their educations. Such erroneous conceptions are referred to as alternative conceptions or misconceptions (Artdej et al., 2010). Demerouti et al. (2004) demonstrated that students face difficulties in learning about acids and bases which are foundational knowledge for properly understanding buffer solutions. The difficulties in learning about buffer solutions are exacerbated by the fact that students struggle in learning about chemical equilibrium (Van Driel & Gräber, 2002).

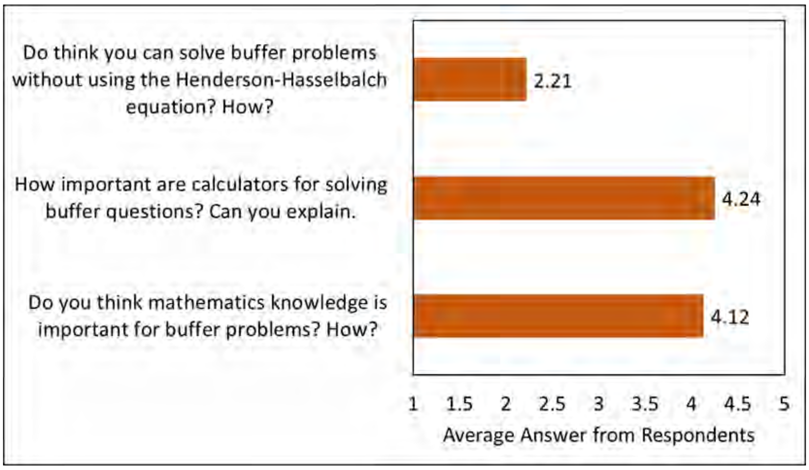

Figure 2
Short-answer questions and average answers from respondents based on the rubric

While the questions were open-ended our rubric scored the student responses on the same scale as the Likert-type questions in which a higher score reflects greater agreement with 1 as the lowest value (maximum disagreement) and 5 as the highest value (maximum agreement).

Three of our open-ended questions (Fig. 2) were developed to evoke student feelings about the importance on math and the Henderson-Hasselbach equation in solving buffer solution questions. These questions were evaluated using a rubric that scaled responses from 1 to 5 with an increasing score positively correlating with an agreement to the premise of the question. Here again, the data suggest that students show a heavy reliance on mathematical algorithmic problem solving and calculator use when solving buffer problems. Additionally, students share a widespread belief that they cannot solve buffer problems without the use of the Henderson-Hasselbalch equation. Student success in undergraduate chemistry classes has been correlated with mathematical ability (Bain et al., 2014) and their performance in math classes in high school is a good predictor of their success in college (Vulperhorst et al., 2018). When teaching buffer solutions instructors often focus on arithmetic calculations in their teaching and on course-assessments thus leading students to believe that solving buffer solutions problems algorithmically is the same as developing conceptual understanding of the topic at the sub-microscopic representational level. Some instructors equate successfully solving algorithmic chemical problems with the development of conceptual understanding and therefore promote rote-learning leading to poor knowledge construction (Wilson, 1994).

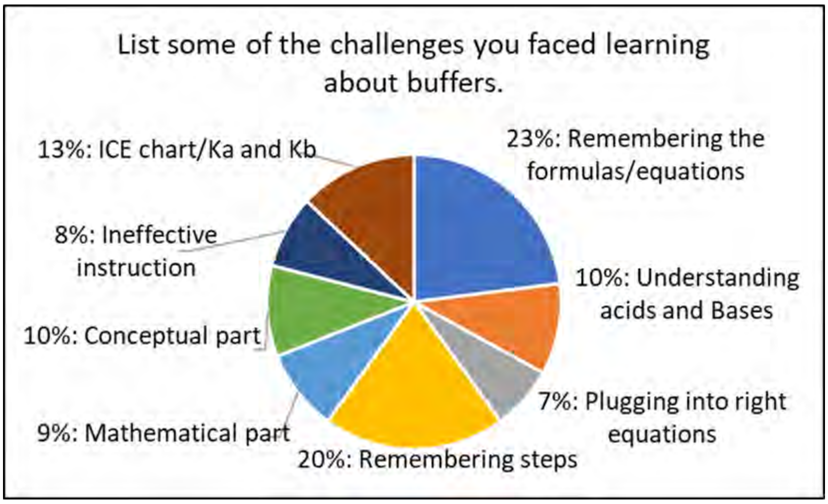

Figure 3
Student responses to open-ended questions about the challenges they faced in learning about buffers were broken down into eight principal categories

The distribution of these responses was fairly uniform, but remembering formulas and the steps of their algorithms were dominant responses.

Open-ended questions allowed students to reveal their perceptions of the challenges they face in solving buffer solutions problems. Their responses were categorized as displayed in Figure 3. 23% of the research participants reported that remembering the formulas and equations related to buffer problems is challenging and 20% report that remembering the steps for solving buffer problems is an obstacle to learning. It is noteworthy that this population of students which comprises 43% of the total rely on memorization and rote-learning for solving buffer problems. Science educators advocate conceptual understanding and meaningful learning of chemistry topics over such rote learning mechanisms as we see here. Furthermore, 7% of participants report that they struggle with plugging numbers into the correct equation and 13% of them have difficulties with ICE charts and equilibrium constants and their expressions. A small fraction of the students, 9%, suggest that buffer problems are challenging because of the mathematical part of the solution. Orgill and Sutherland (2008) found that when solving buffer problems chemistry students approach them as math problems ignoring any consideration of the chemical species involved in the buffer system. Additionally, they found that students approach problems mechanically and apply mathematical algorithms without understanding the reasons for their approach.

Some of the participants, 8%, feel that buffer problems are challenging because of the ineffectiveness of their instruction which primarily followed a lecture format. It is noteworthy that 10% refer to the understanding of acids and bases and another 10% suggest that lack of conceptual understanding as obstacles to learning about buffer problems. One of the major obstacles to learning about buffer solutions is that students

cannot visualize what is happening at the sub-microscopic level (Orgil & Sutherland, 2008). Learning concepts related to aqueous solutions, including buffer solutions, is challenging for students and they develop alternative conceptions about such topics (Damanhuri et al., 2016). Acids-base concepts are considered especially difficult for students to learn and master (Lin et al., 2004) which is consistent with our findings.

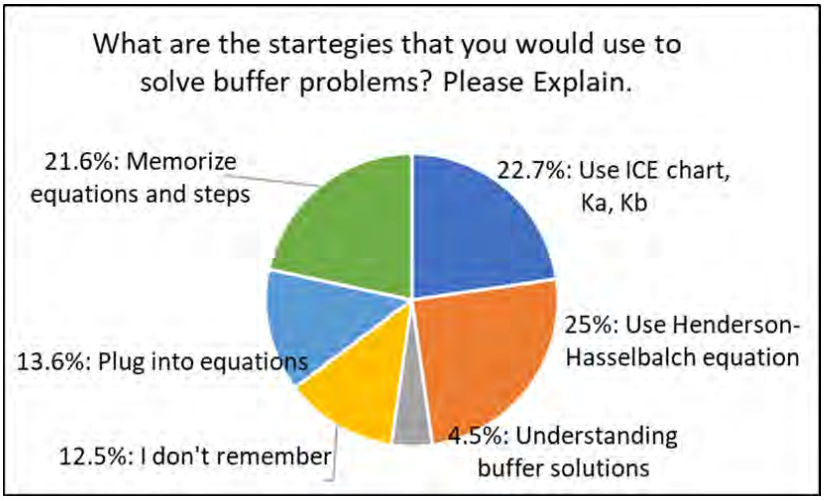

Figure 4
Student responses to open-ended questions about the strategies they used to solve buffer problems fell into five basic categories

Using charts and equations were the overwhelmingly dominant responses.

Additional open-ended questions enabled students to share their strategies (Fig. 4) for solving buffer problems. A total of 48% of respondents reported using ICE charts, equilibrium constants, and the Henderson-Hasselbalch equation to solve buffer solutions problems. About 22% of students rely on memorizing equations as their principal strategy and another 14% simply plug numbers into equations as their tool for approaching buffer solutions problems. Additionally, 12.5% percent of students do not remember how to solve a buffer solutions problem. Alvarado et al. (2015) report that students experience difficulties in differentiating the acidity of a molecule from the pH of a solution, acid strength or concentration of a solution.

It was encouraging that 4.5% of our study participants rely on understanding buffer solutions as a way of solving this type of problem. Chemistry learning in general and certainly buffer related problems require understanding, differentiating, and relating of the three levels of representations: symbolic, macroscopic, and sub-microscopic (Johnstone, 2010). To achieve conceptual understanding, students should be able to relate the three representations of buffers, from the symbolic of chemical equations, the observed macroscopic effect due to addition of acids and bases, and the processes taking place at the particulate or sub-microscopic level (Treagust & Chandrasegaran, 2009).

These challenges are consistent with the nature of learning abstract chemistry concepts that require understanding of symbols, laws, formulas, as well as the ability to interpret such concepts and often result in the development of alternative conceptions (Sendur et al., 2011).

CONCLUSION

The data obtained from this investigation indicate that students face a variety of significant difficulties in learning about buffer solutions. Our undergraduate participants relied heavily on algorithmic problem solving, calculator use, and plugging numbers into equations instead of depending on the development of conceptual understanding to solve buffer solutions problems. Students consider learning about buffer solutions to be an arduous and complex process that involves complicated calculations. Students underscore the importance of the Henderson-Hasselbalch equation for solving buffer problems in contrast to the practice of analytical chemists who use conceptual knowledge and equilibrium constants in their approach to solving buffer problems. It is evident that we are not adequately training students to think like chemists, but instead are teaching them rote solutions for complex problems.

Our data show that students face challenges in learning about buffers due to their dependence on the memorization of formulas, and the myriad steps involved in solving buffer-related problems. Rote learning can hinder the development of conceptual understanding and meaningful learning in students. The strategies that students use to solve buffer-related problems can be viewed as additional obstacles to the learning process since they rely on memorization, plug and chug, and algorithmic problem-solving.

To improve student learning and understanding of buffer solutions we, as instructors, need to identify and address the challenges students face as well as the alternative conceptions they develop when learning about buffer solutions. Additionally, improving meaningful learning and preventing rote-learning should be a goal of every chemistry instructor. We suggest that instructors consider designing active learning environments that immerse students in the knowledge construction that will lead to improved conceptual understanding and prevent the development of alternative conceptions. Nurturing students' competencies to address and relate the three levels of representation and understanding of symbols, laws and formulas, as well as their interpretations of these concepts, can lead to full conceptual understanding of buffer solutions thus improving student performance and success. A suitable future study would involve modifying instructional approaches to a constructivist and collaborative approach in teaching about buffer solutions and studying the effects of the intervention on students' learning and understanding.

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